Overview of String Phenomenology

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Outline

- Motivation/Introduction/Generalities
- Heterotic models
- D-brane models, F-theory models
- Moduli stabilization and supersymmetry breaking
- Open questions
- Conclusions

String Phenomenology

- String theory describes gravitational and gauge interactions in a unified framework, consistent at the quantum level

- If string theory is realized in Nature, it should be able to describe a very specific gauge sector: Standard Model

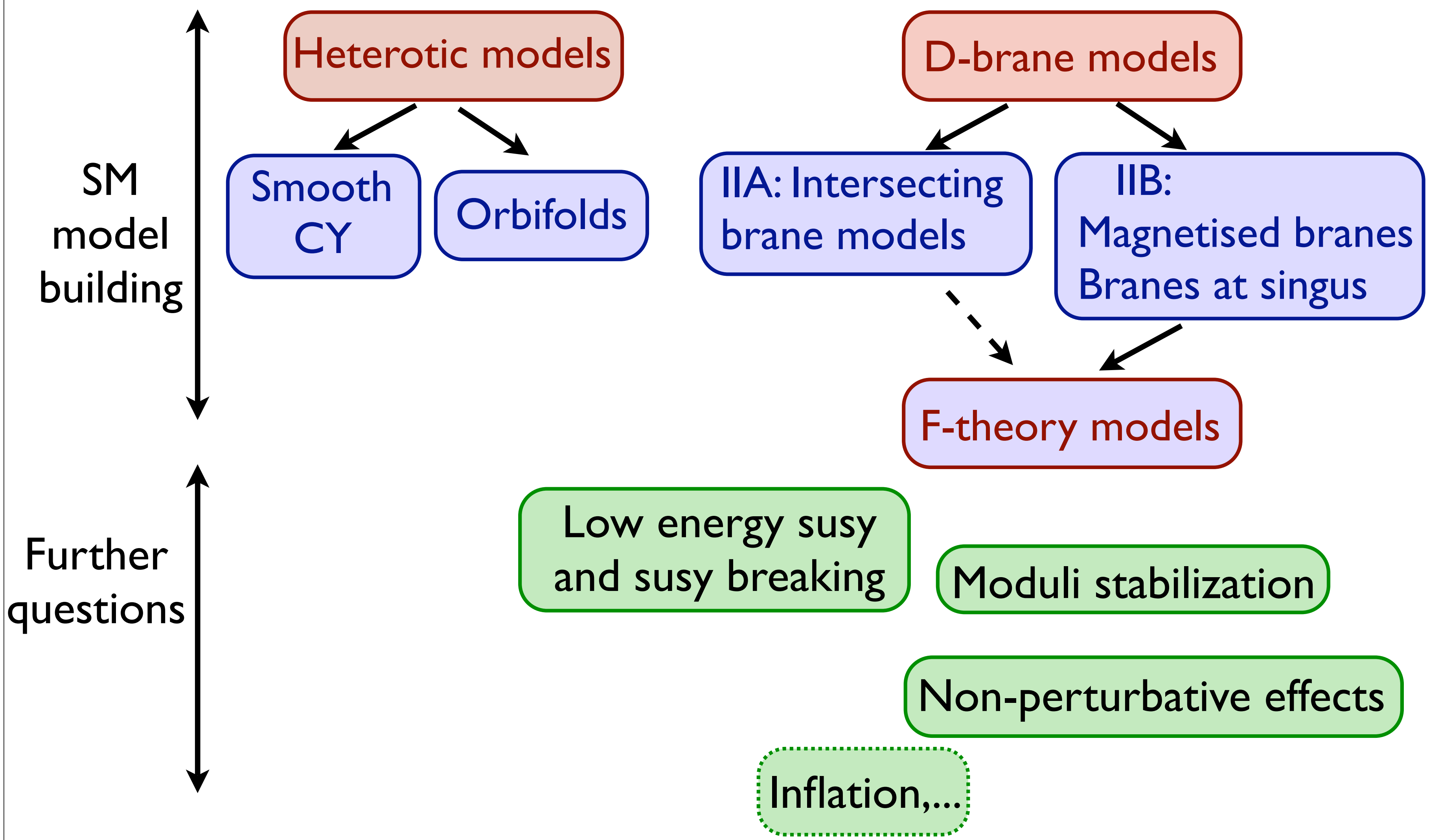
- Aim of String Phenomenology:

  - Determine classes of constructions with a chance to lead to SM
    Non abelian gauge interactions, replicated charged fermions, Higgs scalars with appropriate Yukawa couplings, ...

  - Within each class, obtain explicit models as close to SM as possible with the hope of learning more about the microscopics of SM in string theory

- Old program, yet continuous progress
  Moduli stabilization, non-perturbative effects, ...

A road map in String Phenomenology

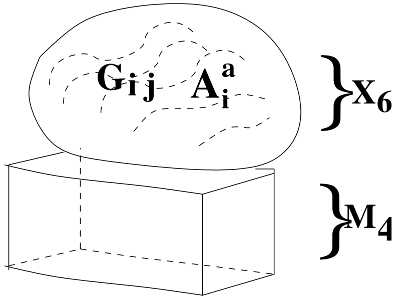


In this talk we follow a particular path in the flowchart

Heterotic string models

[Candelas, Horowitz, Strominger, Witten, '85]

- The 10d heterotic string has as effective theory 10d N=1 sugra coupled to E8xE8 (or SO(32)) gauge multiplets
- Compatification: six extra dimensions parametrize small Calabi-Yau space, on which we also turn on a non-trivial gauge field background



- Gauge group is broken by gauge background
Possible to break down to something close to SM gauge group

- 4d charged chiral fermions from KK reduction of 10 gauginos.
Number of families fixed by topological data

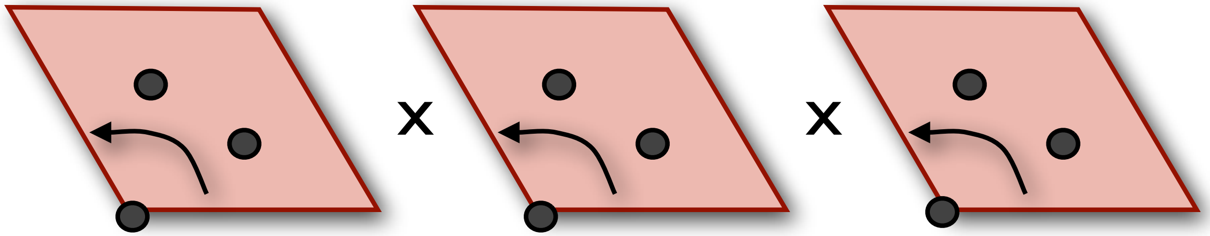
- Within this general class, very explicit models close to (MS)SM

[e.g. Ovrut et al.]

Heterotic String Orbifolds

- A very tractable version is provided by toroidal orbifold models
- Compatification space is quotient of T^6 by discrete symmetry

Ex: T^6/Z_3



- Gauge background is trivial except around orbifold singularities

Discrete gauge transformation while moving around fixed point

- Models very close to (MS)SM have been explicitly constructed and studied

[Talks by Hebecker, Ratz, ...]

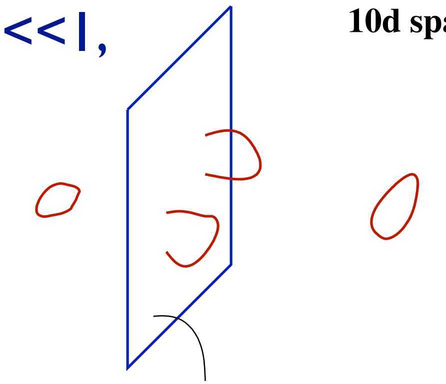
- Geometric intuitions very helpful:
Partial gauge breaking at orbifold points/planes

- Need effective field theory arguments to remove exotics, break some gauge symmetries

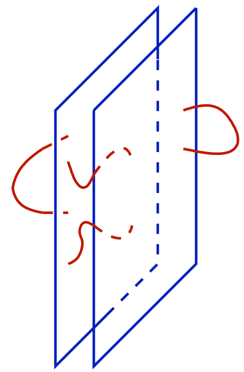
D-branes [Polchinski, '95]

- In this talk, focus on D-brane models in type II string compactifications

- At weak coupling and small numbers, g_s N <<1, treat in the probe approximation



- Described as subspaces of 10d space on which open strings can end
- N overlapping D-branes develop enhanced U(N) gauge symmetry



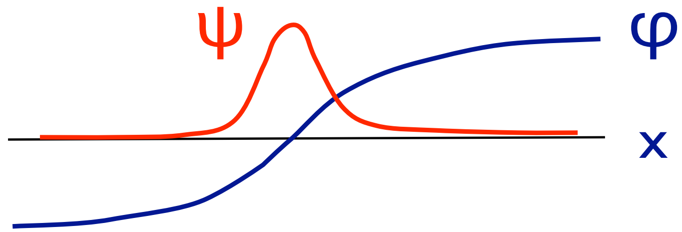
- Effective action is U(N) (super) Yang Mills

- Adjoint scalars = translational Goldstones
  vevs = brane positions
  Adjoint fermions = Goldstinos

Chirality

- Chirality is a crucial criterion discriminating which string/brane configurations can lead to models of particle physics
- Mechanism for chirality in string th. can be understood in field th.

5d fermion coupled to scalar kink has 4d chiral fermion zero mode



- Domain wall fermions in lattice gauge field theories
- Fermion localization in extra dimensions in BSM phenomenology

- Different string realizations lead to different string constructions
- Different string realizations are dual to each other

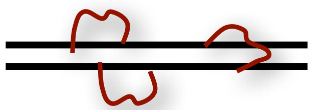
Not that "different"!

D-branes and chirality

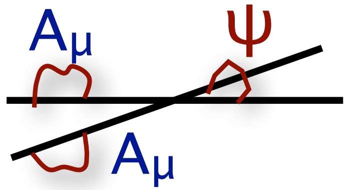
T-dual

Intersecting D-branes

Non-trivial kink for scalar describing brane separation



$\varphi = k\, x$ →



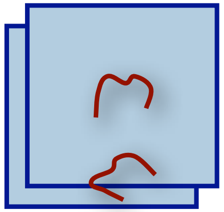
4d chiral fermion at intersections

Magnetised D-branes

Non-trivial kink for gauge component

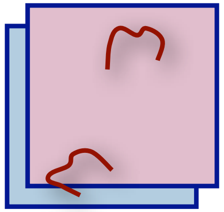
D-branes wrapped on 2d plane with different U(1) magnetic flux

U(2)



$\langle F\rangle = F\,\sigma_3$ →

$A_5 = F\, x_4$

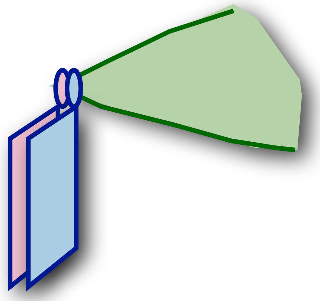


4d chiral fermion from off-diagonal in $U(2) \rightarrow U(1) \times U(1)$

Mechanism is as in heterotic: chirality from gauge background

D-branes at singularities

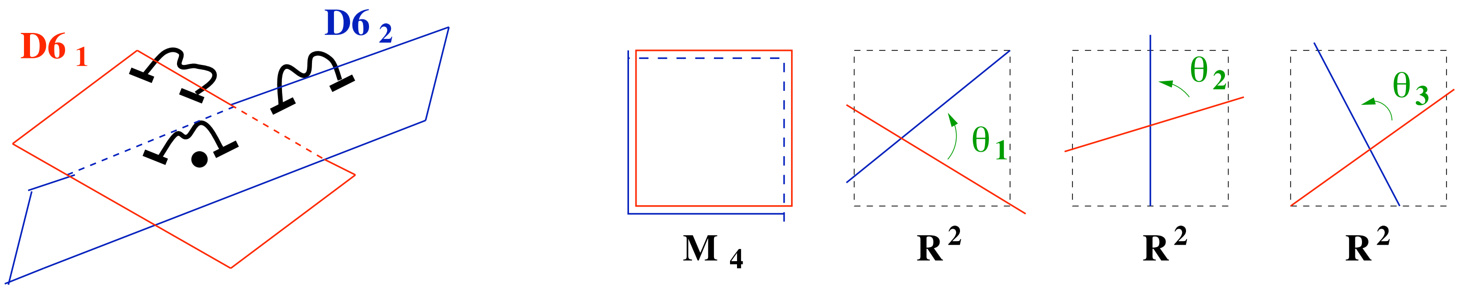
Limit case of magnetised branes with gauge background non-trivial only around fixed points



Intersecting D6-branes in type IIA

[Berkooz, Douglas, Leigh,'96]

- Consider type IIA string theory with two stacks of D6-branes (hence 7d subspaces) intersecting over a 4d subspace of their volumes



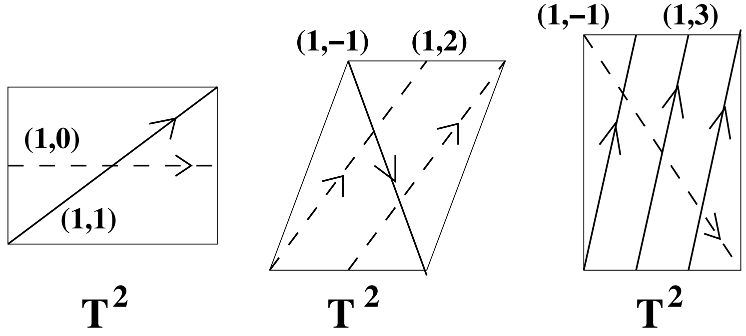
- Three sectors of open strings
  - $D6_1$-$D6_1$: $U(N_1)$ on 7d plane 1
  - $D6_2$-$D6_2$: $U(N_2)$ on 7d plane 2
  - $D6_1$-$D6_2$: 4d chiral fermion in $(N_1,\overline{N}_2)$ on 4d intersection

- Chirality is a consequence of the geometry of the intersection
  e.g. two D5's intersecting over 4d leads to non-chiral fermions
  Need intersections in all three complex planes

Intersecting brane worlds

[Blumenhagen, Gorlich, Kors, Lust; Aldazabal, Franco, Ibanez, Rabadan, AU; '00]

- To obtain 4d gravity, need to compactify, e.g. on on $T^6 = T^2 \times T^2 \times T^2$



- Configurations of D6-branes in sets of N_a $D6_a$-branes wrapping 3-cycles Π_a described as products of 1-cycles (n_a^i, m_a^i) on each $(T^2)^i$

Gauge group $\prod_a U(N_a)$

Chiral fermions $\sum_{a,b} I_{ab}\,(N_a, \overline{N}_b)$

$$I_{ab} = (n_a^1 m_b^1 - n_b^1 m_a^1) \times (n_a^2 m_b^2 - n_b^2 m_a^2) \times (n_a^3 m_b^3 - n_b^3 m_a^3)$$

Intersection number = geometric origin of family replication!

- Generalizes to D6-branes on intersecting 3-cycles on general CY

Towards the SM

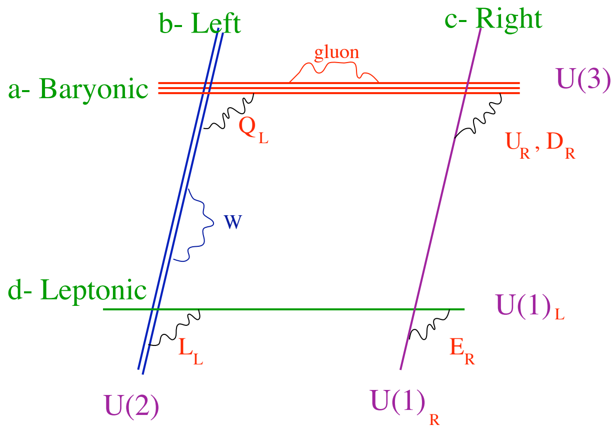
- A simple road to SM
  (not unique, e.g. see later for GUTs)

[Ibanez, Marchesano, Rabadan; Cremades, Ibanez, Marchesano;'01]

Introduce four stacks of D6's a,b,c,d

$$U(3)_a \times USp(2)_b \times U(1)_c \times U(1)_d$$

$$I_{ab} = 3 \longrightarrow \quad Q_L$$
$$I_{ac} = -3,\ I_{ac'} = 3 \longrightarrow \quad U_R,\ D_R$$
$$I_{db} = 3 \ \longrightarrow \quad L$$
$$I_{dc} = -3,\ I_{dc'} = -3 \longrightarrow \quad E_R,\ \nu_R$$



Spectrum of SM with hypercharge $\quad Y = \frac{1}{6}Q_a - \frac{1}{2}Q_c - \frac{1}{2}Q_d$

- Explicit realization of this structure e.g. in toroidal models

N_α	(n_α^1, m_α^1)	(n_α^2, m_α^2)	(n_α^3, m_α^3)
$N_a = 3$	(1,0)	(1,3)	(1,-3)
$N_b = 1$	(0,1)	(1,0)	(0,-1)
$N_c = 1$	(0,1)	(0,-1)	(1,0)
$N_d = 1$	(1,0)	(1,3)	(1,-3)

Some phenomenological properties

[Aldazabal, Franco, Ibanez, Rabadan, AU; ...]

- Gauge couplings

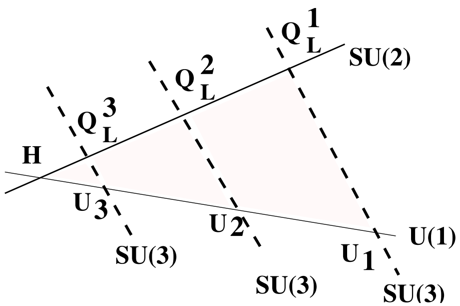
  A priori no natural unification at string scale

  Each coupling depends on wrapped volume $$\frac{1}{g_a^2} = \frac{V_{\Pi a}}{g_s}$$

  Can try GUT model building, see later

- Yukawa couplings

  Mediated by open string worldsheet instantons $Y_{jk} \simeq e^{-A_{Hjk}+i\phi_{jk}}$



  Exponential dependence potentially explains fermion mass hierarchy

- String scale

  - Susy models, can 'choose' string scale (until susy breaking is specified)

  - Non-susy models, can alleviate hierarchy by large volume [ADD'98]

- Proton decay

  In SM models, perturbatively forbidden by $U(1)_a$ baryon number

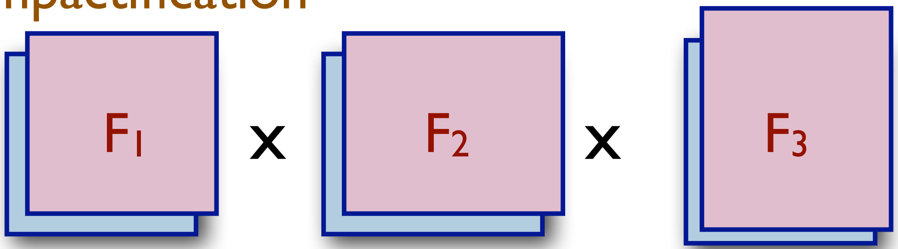
  Violated by instantons, just like in SM

Magnetized type IIB models

- Chirality from magnetic fields on all dimensions of D9-branes

[Bachas '95; Angelantonj, Antoniadis, Dudas, Sagnotti]

Ex: Toroidal compactification



D9$_a$-branes labeled by (n_a^i, m_a^i)

D-branes wrapped n^i times on each $(T^2)^i$ with m_a^i units of magnetic flux

Gauge group $\prod_a U(N_a)$

Chiral fermions $\sum_{a,b} I_{ab}\,(N_a, \overline{N}_b)$

$$I_{ab} = (n_a^1 m_b^1 - n_b^1 m_a^1) \times (n_a^2 m_b^2 - n_b^2 m_a^2) \times (n_a^3 m_b^3 - n_b^3 m_a^3)$$

Family replication = Zero modes of Dirac operator in magnetic fields

- Can build same models as for intersecting D-branes in IIB side

Convenient for further improvements, like moduli stabilization

Some phenomenological properties

[Aldazabal, Franco, Ibanez, Rabadan, AU; ...]

- Gauge couplings

  Unified higher-dimensional gauge group, broken by magnetic field

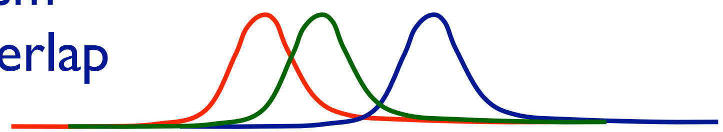
  Unification modulo threshold corrections

  Can try GUT model building, see later

- Yukawa couplings

  Arise from purely field theory mechanism

  Overlap of zero mode wavefunction overlap



$$Y_{jk} \simeq e^{-A_{Hjk} + i\phi_{jk}}$$

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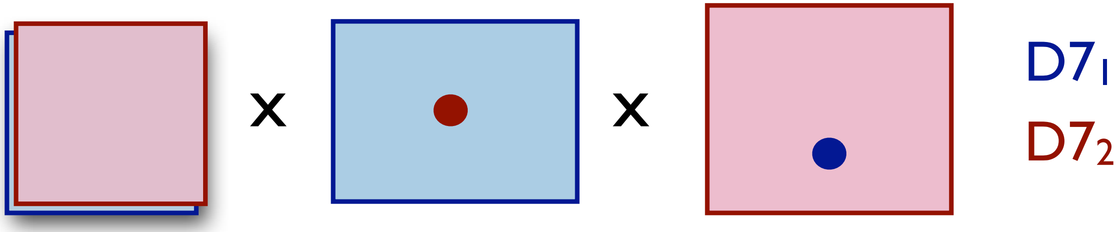
D7-brane models in type IIB

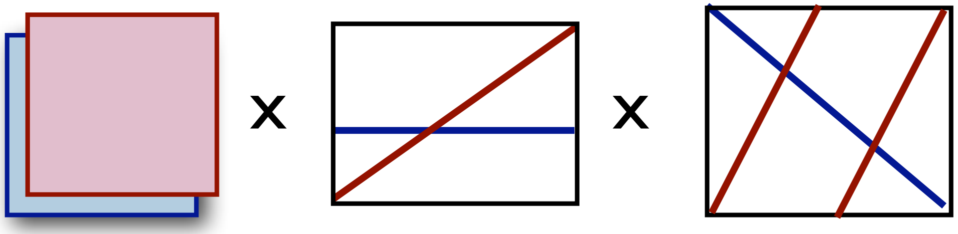
- Class includes configurations with intersecting D7s with magnetic flux
  - Essentially, meaning of entries (n,m)=(0,1)

Gauge groups on 4-cycles



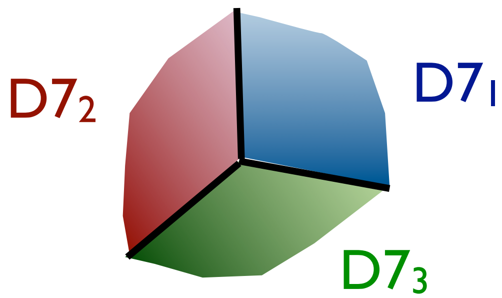
- Each D7 wraps a 4-cycle, two D7's intersect over 2-cycles

Chiral matter on 2-cycles



- Yukawa couplings localize on points

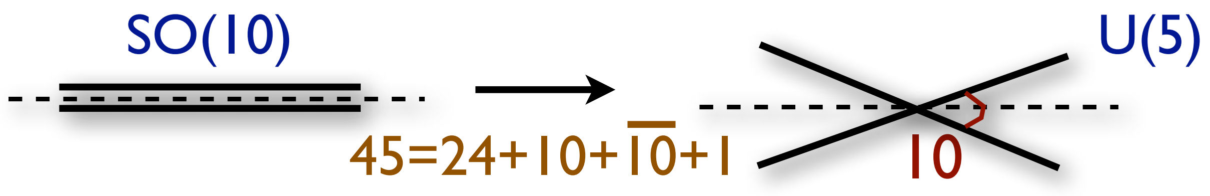
Only place where wavefunctions overlap



GUTs, D-branes and F-theory

- Can build SU(5) GUTS using 5 overlapping D-branes

  Matter in 10 from open strings between brane and "orientifold image"



- Only problem is absence of perturbative 10.10.5 Yukawa

  Forbidden by U(1) factor in U(5) on the branes

- Can be generated by non-perturbative effects: D-brane instantons

  [Blumenhagen, Cvetic, Weigand; Ibanez, AU; '07]

  Possibly, but need to avoid excessive suppression

- Yukawas can be made of order one by using F-theory
  Non-perturbative generalization of IIB, including 7-branes with richer "group theoretical" properties

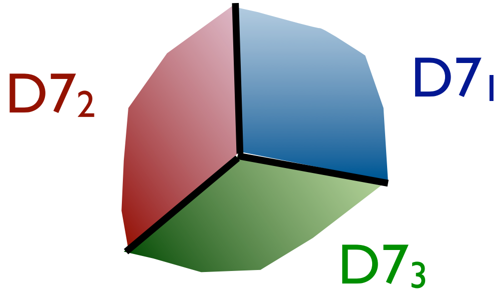
Yukawas in F-theory GUTS [Beasley, Heckman, Vafa]

- In IIB D7's, 12-23-31 Yukawa from local enhanced U(N1+N2+N3)

  $U(N_1+N_2+N_3) \rightarrow U(N_1) \times U(N_2) \times U(N_3)$

  $\text{Adj} \rightarrow \text{Adj}_1 + \text{Adj}_2 + \text{Adj}_3$

  $+ (N_1,\overline{N}_2) + (N_2,\overline{N}_3) + (N_1,\overline{N}_3) + \text{cc.}$



- With orientifolds, $10.\overline{5}.\overline{5}$ Yukawa from local SO(12)

  $SO(12) \rightarrow SO(10) \times U(1) \rightarrow SU(5) \times U(1) \times U(1)$

  $66 \rightarrow 45 + 10 + \overline{10} + 1 \rightarrow 24 + 10 + \overline{5} + \overline{5} + \text{cc} + \text{singlets}$

- In F-theory, 7-branes with local E6 enhancement produce 10.10.5

  $E6 \rightarrow SO(10) \times U(1) \rightarrow SU(5) \times U(1) \times U(1)$

  $78 \rightarrow 45 + 16 + \overline{16} + 1 \rightarrow 24 + 10 + 10 + 5 + \text{cc} + \text{singlets}$

F-theory allows to reconcile brane model building and GUT ideas

Local F-theory models

[Donagi, Wijnholt; Beasley, Heckman, Vafa]

- Bottom-up approach [Aldazabal, Ibanez, Quevedo, AU; '00]

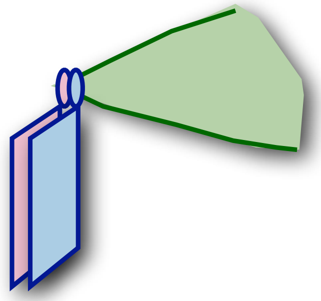
  Build local configuration of D-branes, later embed in compact space

- Ingredients

  - SU(5) 7-brane wrapped on a "small" 4-cycle S_{GUT}

    " del Pezzo surface": Blowup of a singularity

  - U(1) hypercharge magnetic flux breaks to SM



  - Other 7-branes intersect S_{GUT} over 2-cycles, leading to chiral matter

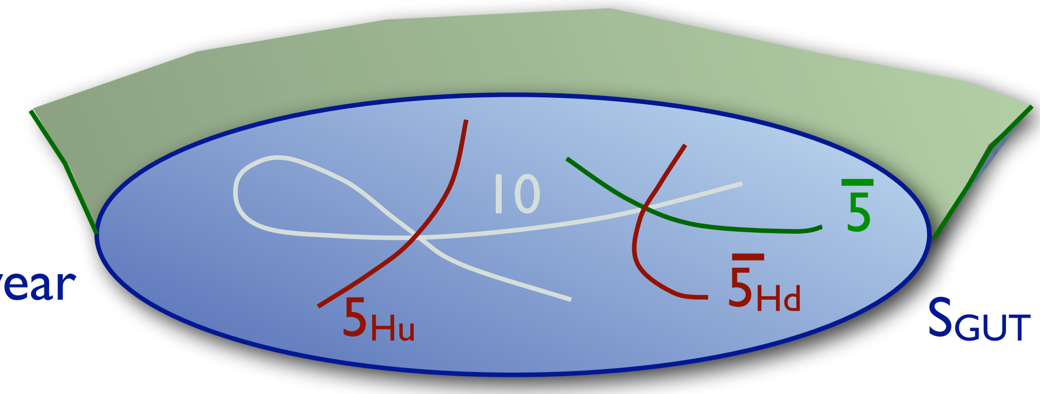
    SM fermions from 2-cycles with no hypercharge flux: SU(5) multiplets

    Higgses from 2-cycles with hypercharge flux: DT splitting

  - Yukawas from points where matter 2-cycles intersect

- Intense work in last year

  [Heckman, Vafa; ...]



Global GUT models

- In type IIB orientifolds [Blumenhagen, Braun, Grimm, Weigand, '08;]

  Type IIB analog of F-theory GUTS
  Build 6d CY compact space with a local del Pezzo 4-cycle
  Wrap D7-branes to reproduce local structure of GUT model
  Satisfy certain global consistency conditions (Gauss law)
  Require existence of non-perturbative instantons generating 10.10.5

  ⇒ Explicit model with 3 families

- In F-theory [Marsano, Saulina, Schafer-Nameki, '09]

  7-branes source complex coupling τ, which varies over 6d space
  Geometrize as 2 extra T^2 dimensions ⇒ 8d compact space
  7-brane magnetic field becomes 4-form flux in this 8d space
  Build 8d compact CY space with local patch reproducing F-theory GUT
  Suceed in building the geometry, but flux is still difficult to handle

  ⇒ On the way to explicit model with 3 families

Moduli stabilization and fluxes

- Simplest compatifications ⇒ moduli, massless scalars w/ no potential

  e.g. parametrize sizes of 2- and 3-cycles in CY (Kahler and complex)

- Moduli stabilization from fluxes in the compactification

  Field strength fluxes on cycles, geometric fluxes, ...
  Nontrivial dependence on moduli ⇒ scalar potential

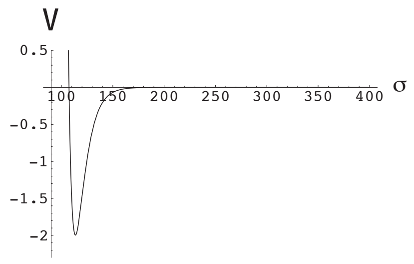
  [Dasgupta, Rajesh, Sethi; Giddings, Kachru, Polchinski; ...]

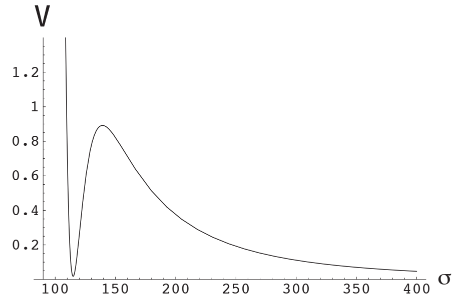
- Explicit models of (MS)SM with (partial) flux moduli stabilization

[Blumenhagen, Lust, Taylor; Cascales, AU; Camara, Font, Ibanez; Villadoro, Zwirner; '03-'06]

Moduli stabilization & susy breaking in Minkoswki (full stab. in AdS)

Going to dS is open question, with interesting but not yet explicit proposals





[KKLT '03]

Fluxes, susy breaking and soft terms

- Appealing (not unique) scenario: Susy MSSM D-branes and non-susy flux
- Soft terms arise from effect of non-susy flux on susy D-branes

  Explicitly computable using D-brane world-volume action in general supergravity background, or using 4d effective theory approach

  [Grana; Camara, Ibanez, AU; Lust, Mayr, Reffert, Stieberger; '03-'04]

- Flux components work as vevs for auxiliary fields of chiral multiplets of (complex structure) moduli

  ⇒ Realization of gravity-mediated susy breaking

  - Flavour problem: Decoupling of flavor physics and soft terms
    Geometrization squark masses determined by intersection angles
  - μ-problem: susy components of flux induce it on the branes

- Very explicit discussion of susy spectrum etc is possible in specific models

  e.g. in 'large volume compactifications' [Quevedo et al '06-'07]

  F-theory [Aparicio, G.Cerdeño, Ibáñez, '08]

Conclusions

- It is remarkable that there are string models so close to (MS)SM
- Unique theory, yet many vacua

  Many choices of data of compactification to 4d
- Rules are very well defined

  Many examples of things which are just not possible
  - Very large representations ⇒ e.g. no 126 of SO(10)
  - Bounds on number of branes ⇒ rank of gauge groups

  Many examples of things not possible in a particular class
  - No SO(10) GUT on weakly coupled D-brane models
- Role of geometric intuition: Geometrization of SM structures
- Role of modular structures:

  Relatively independent building blocks for SM, susy breaking, inflation, moduli stabilization, ...

What is it good for?

- Many realistic vacua: No unique testable prediction

Each particular consistent realistic model is probably wrong
But some general lessons may be right and key to the UV of SM

- New scenarios (in UV complete theory):
  Extra dimensions, brane world, warping, ...

- Plausible patterns within each
  e.g. Low energy susy and susy breaking soft terms

- Smoking guns for some scenarios (±contrived)
  e.g. string resonances in TeV scale models

- Impact of LHC results?

- Expect continuous progress in understanding the UV of SM